The Effects of Fertilization on the Early Growth of Planted Seedlings: A Problem Analysis

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EXECUTIVE SUMMARY

Empirical research data indicate inconsistent responses to fertilization of planted seedlings. To explain these inconsistencies, considerable process-oriented research must be undertaken to improve our understanding of the effects of factors such as soil and aerial microclimate, seedling morphology and physiology, and soil nutrient availability on the response potential of fertilized seedlings. In the interim, however, a number of points can be summarized:

- Fertilization of interior spruce seedlings at the time of planting has been shown to reduce the severity of planting check. Seedling height responses of 15-20 cm are the "best" achieved in trials to date. However, available response data may underestimate seedling response potential if the beneficial effects of combined fertilization/site preparation/vegetation control treatments, which have been documented elsewhere, can be demonstrated in the interior of British Columbia.
- Adequate soil moisture is a prerequisite to seedling responsiveness to fertilization. Warm, dry weather during the period following fertilization may have a negative impact on seedling survival. Fertilization under these conditions merely aggravates stress in severely stressed seedlings, primarily as a result of the osmotic effect of high salt concentrations.
- The removal of surface organic material and topsoil by mechanical site preparation (e.g., windrowing, blade scarification) may increase seedling fertilization response potential because of nutrient depletion, soil warming and destruction of competing vegetation. The response potential to fertilization at planting may be somewhat lower on broadcast burned sites because of increased nutrient availability during the short period immediately following burning.
- To minimize the negative effects of competing vegetation, seedling fertilization should only be contemplated on sites that have been recently site prepared.
- The largest and most consistent responses to fertilization at planting have been obtained with container nursery stock. Although other factors may also be involved, the difference in fertilization response potential between container and bareroot seedlings appears to be largely attributable to the higher root growth capacity generally obtained with the former stock type.
- Initial seedling size has little effect on fertilization response potential, provided planting stock is in good physiological condition.
- Application of soluble inorganic fertilizers at the time of planting generally reduces survival and does not improve the early growth performance of interior spruce seedlings.
- Although fertilizer source x placement method interactions have been documented, response differences between commonly used slow-release fertilizers (i.e., Agriform, Osmocote, Nutricote) appear to be insignificant when fertilizers are broadcast at equivalent nitrogen application rates. However, the cost of Agriform is currently 40-50% higher than the other two products.
- Although commonly used slow-release fertilizers contain nitrogen, phosphorous and potassium, there is little evidence to indicate that interior spruce seedlings respond to nutrients other than nitrogen.
- Of the methods tested to date, broadcast application is generally the most effective means of applying fertilizer to seedlings at the time of planting. However, broadcast application of fertilizer may stimulate the growth of competing vegetation and thus partially negate the favourable effects of fertilizer on planted seedlings. Studies elsewhere have reported the beneficial effects of combining fertilization at planting with intensive site preparation and vegetation control.
- Interior spruce fertilizer response data indicate that little, if any, additional growth is obtained at high application rates of slow-release fertilizer (e.g., > 30 g per seedling of Osmocote or Nutricote). Higher rates may stimulate vegetation competition and, under conditions of moisture stress, may have a negative impact on seedling survival.

- Fertilization of interior spruce seedlings at the time of planting does not appear to increase the incidence of fall frost damage significantly, except possibly at high elevations. Rather, fertilized seedlings may be less susceptible to winter injuries (i.e., extreme cold and/or desiccation) than unfertilized seedlings.
- Fertilization at the time of planting is an expensive and inefficient method of supplying nutrients to seedlings. Incorporation of slow-release fertilizer into the plug at the time of sowing, late-season nutrient loading, and injection of fertilizer into the plug at the time of lifting are nutrient delivery alternatives that merit investigation.

PREFACE

A substantial amount of seedling fertilization research has been undertaken in British Columbia and elsewhere in recent years, but the approach to the subject has been fragmented. Results have been inconsistent and much of the work has not been reported in the scientific literature, a fact which has restricted the application of knowledge to the subject area.

The purpose of this report is to review and summarize available seedling fertilization information to identify promising treatments and treatment combinations; and to make specific recommendations regarding the direction and scope of future seedling fertilization research and operations. Throughout the report, special reference is made to interior spruce because of its pre-eminent position within the provincial reforestation program and its special problems with respect to "planting check". However, many of the findings may apply equally well to other conifer species.

ACKNOWLEDGEMENTS

Much of the information contained in this report was drawn from the unpublished reports and collected data of research scientists and operational forestry and nursery personnel. To these people, too numerous to list here, I am especially grateful. Many of my colleagues have made valuable suggestions regarding the content and organization of this report and to them I extend my thanks.

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1 INTRODUCTION

The concept of fertilizing planted seedlings to stimulate growth during the establishment phase of plantation development is not new. Research has demonstrated that enhancement of seedling growth by nutrient additions can result in permanent production gains (Snowdon and Waring 1984). Fertilization at or near the time of planting is standard practice on many forest sites in Australasia, Great Britain, and the southeastern United States (Everard 1974; Ballard and Pritchett 1975; Ballard 1978; Waring 1981).

Although a substantial amount of seedling fertilization research has been undertaken in western North America, the approach to the subject has been fragmented. Results have been inconsistent and the relative benefits of various treatments and treatment combinations on specific site types are still unclear. Moreover, much of the work has not been reported in the scientific literature, a fact which has restricted the application of knowledge.

The objectives of this problem analysis are:

1. to review and summarize available seedling fertilization information, including
    i. knowledge accumulated by operational forestry and nursery personnel;
    ii. information available from research (EP) and silviculture (Sx) trials (both published and unpublished) undertaken in British Columbia;
    iii. information available from the scientific literature that, although obtained from experiments conducted outside British Columbia, is considered pertinent to the subject area.
2. to make specific recommendations regarding the direction and scope of future operational seedling fertilization projects and research trials in British Columbia.

Interior spruce (*Picea glauca* [Moench] Voss and *Picea engelmannii* [Parry], or the naturally occurring hybrid of these species) is the primary species of interest. This species currently represents 55% of the annual planting program in British Columbia. Unfortunately, interior spruce seedlings often grow slowly in the years immediately following planting (Mullin 1963, 1964; Dobbs 1972; Stiell 1976; Vyse 1981), a phenomenon which has stimulated considerable interest in investigating means by which the duration and severity of "planting check" can be minimized.

Accumulated evidence indicates that there are two phases to planting check: the first being due to moisture stress, the second to nutrient deficiency (Burdett *et al.* 1984). Observations by Burdett *et al.* (1984) indicate that the first phase can be eliminated by using nursery stock with high root growth capacity (RGC), and the second by applying slow-release fertilizer to seedlings at the time of planting. Alternative methods of supplying planted seedlings with nutrients (e.g., incorporation of slow-release fertilizer into the soil mix at the time of container sowing, and late-season fertilization in the nursery) presumably also have potential for stimulating seedling outplanting performance.

Many nursery cultural practices have an influence on seedling nutrition and although an adequate mineral nutrient level is no guarantee of vitality, seedling nutrient status is generally positively related to growth after outplanting (Landis 1985). However, the effects on survival and growth are largely indirect because of the impact of nutrition on many seedling morphological and physiological characteristics. Therefore, discussion of nursery stock nutrition (except late season fertilization) is beyond the scope of this paper.

2 FERTILIZATION OF SEEDLINGS AT THE TIME OF PLANTING

2.1 Fertilizer Source

In Australasia and the southeastern United States, applications of highly soluble inorganic fertilizers at plantation establishment generally result in favourable growth response (Ballard 1978; Tiarks and Haywood 1981, 1986; Waring 1981; Crane 1982). However, experience on northern temperate and boreal forest sites has shown that readily soluble sources generally increase mortality and do not improve the early growth performance of conifer plantations (White 1960; Smith *et al.* 1966; Leikola and Rikala 1974; Sutton 1982).[1,2,3,4] Increased mortality is primarily a consequence of the osmotic effect of high salt concentrations in the rooting zone. The responsiveness of seedlings to soluble inorganic fertilizers is limited by the combined effects of the movement of added nutrients through the upper solum, nutrient uptake by competing vegetation, and the inability of root systems of newly planted seedlings on northern temperate and boreal sites to use large quantities of nutrients. However, experimental data recently reported by Hass (1987) contradict these findings.

Several types of slow-release fertilizers were developed and tested in the 1950's and early 1960's. Most of these early trials tested various pelleted urea formaldehyde fertilizer resins with different solubility characteristics. As well as reducing the risk of damage to seedling roots and supplying nutrients at rates more in line with seedling nutrient requirements, slow-release pelleted fertilizers showed potential for simplifying the fertilizer operations. Variable results were reported, from significant growth response (Austin and Strand 1960; Rotacher and Franklin 1964; Swan 1965) to slight growth inhibition (Walters *et al.* 1966).

The largest of these trials was initiated in 1959 by the Pulp and Paper Research Institute of Canada, to compare the survival and growth of unfertilized seedlings with those fertilized with a 9.0 g urea formaldehyde/phosphorus fertilizer pellet (28-5-0) at the time of planting. A total of 26 trials were established in four provinces (New Brunswick, Quebec, Ontario, and British Columbia). Species tested were as follows: four species of spruce (20 trials), jack pine (two trials), Douglas-fir (two trials), and two species of larch (two trials). Swan (1965) reported small but significant increases (+9.5%) in 5-year height increments attributable to fertilization in the 13 white spruce trials. Although some of the relative height increases were large (up to 40%), in no case did absolute gains exceed 11 cm, and in most instances amounted to less than 3 cm. It was concluded that although the concept of a slowly soluble, non-toxic fertilizer pellet applied at the time of planting was sound, the pellets were too small to provide sufficiently large supplies of nutrients to increase seedling growth substantially.

Since growth of unfertilized seedlings in these early studies was often poor, fertilizer response could have been limited by the physiological condition of the planting stock. Improvements in nursery culture, keen interest in improving plantation performance, and recent advancements in the manufacture of slow-release fertilizers have rekindled interest in seedling fertilization research in recent years.

Arnott and Brett (1973) reported favourable effects of organic fertilizer (i.e., 4-11-7 hoof-and-horn meal) on the outplanting performance of container-grown Douglas-fir and Sitka spruce seedlings. The fertilizer was placed in a Walter's bullet and dibble-planted 7.5 cm away from the seedlings to allow a slow release of nutrients through the holes and side opening of the bullet. Fertilization had almost doubled the height of Douglas-fir seedlings 3 years after planting (60.5 cm and 34.8 cm for fertilized and unfertilized seedlings, respectively). However, a similar experiment established on a drier site showed no beneficial effects of fertilizer application.

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[1] van den Driessche, R. 1983. Comparison of slow-release and soluble fertilizers applied at outplanting. B.C. Min. For. Lands. EP 946.05. Unpublished data.

[2] Lozinsky, D. 1985. Interior spruce seedling fertilization trial - Salmon Arm. B.C. Min. For. Lands. Sx 84112K. Unpublished final report.

[3] Couch, D. 1987. Fertilization trials - 1985. Riverside Forest Products Ltd. EX-4. Unpublished report.

[4] van den Driessche, R. and A. Vyse. 1982. Comparison of slow release and soluble fertilizer applied to interior spruce at planting. B.C. Min. For. Lands. EP 946.04. Unpublished data.

Most recent studies have used one or more of the following slow-release inorganic fertilizers: 1) Osmocote[5] (18-6-12, 8-9 month release; 17-7-12, 12-14 month release); 2) Agriform[5] (22-8-2 and 20-10-5, 1-2 year release); and 3) Nutricote[6] (16-10-10, 270- and 360-day release).

Osmocote and Nutricote are manufactured by coating soluble, inorganic NPK fertilizers with insoluble resin. The release of nutrients from Osmocote is determined by the thickness of the resin coating. The porosity of the Nutricote prill, and thus the rate of outward nutrient diffusion, is governed by the composition of the resin and the type and quantity of a chemical release agent contained in the coating. Although nutrient release from both products is temperature dependent, nursery cultural experience indicates that a more uniform release rate is achieved with Nutricote.[7] In both products, the form of nitrogen supplied is approximately balanced between ammonium- and nitrate-nitrogen.

Agriform is a slowly soluble, pelleted fertilizer manufactured with urea formaldehyde. Pellet size and the ratio of urea to formaldehyde can be varied to produce products with different N analyses and solubility characteristics.[8]

In comparative studies, Osmocote has generally given a larger shoot growth response than Agriform (Carlson and Preisig 1981).[9] Root growth was also reported to be stimulated more by Osmocote than by Agriform (Carlson and Preisig 1981). However, differences in nitrogen application rate and/or fertilizer placement may have contributed to the superiority of Osmocote in these trials. There appears to be little difference in seedling height response when the products are broadcast (i.e., applied to the soil surface around the base of the seedling) at similar nitrogen application rates.[9] However, at equivalent application rates, the cost of Agriform is presently 40-50% higher than Osmocote.

Two-year height growth response data from comparative experiments with Osmocote and Nutricote indicate there is little difference between these two products.[10,11] However, fertilizer source effects may have been masked by the relative unresponsiveness of the study sites to seedling fertilization (20% increase in height increment over 2 years).

In addition to these well-known slow-release fertilizers, a new product formulated of isobutylidene diurea (IBDU) is also commercially available.[12] IBDU is a product of condensation reaction between urea and isobutyraldehyde. It is a slightly soluble, white crystalline powder with a nitrogen content of 32%. Numerous formulations of slow-release fertilizers can be manufactured by incorporating IBDU with various other nutrients and forming the result into pillow-shaped briquets under high pressure. The briquets marketed in the United States weigh 16 g and contain slow-release formulations of either 14-3-3 with Ca, Mg, Cu, Fe, Mn, and Zn, or 23-2-0 with Mg. Fuller and Meadows (1983) found in studies of horticultural plants that the briquets provided a slow release of nitrogen for about 1 year. Studies sponsored by the fertilizer manufacturer in Japan indicate that under forest conditions the duration of nitrogen release may be substantially longer and that application of IBDU briquets (23-2-0) to native conifers at the time of planting may result in spectacular growth compared with unfertilized seedlings (190% increase in height and diameter growth over 5 years). Application rates up to 70 g N per seedling have been tested with no detrimental effects on survival. However, the additional improvements in growth response obtained above 24 g N per seedling were likely too small to warrant the extra costs involved. In the Pacific Northwest, Atalla (1987) reported that one IBDU briquet (14-3-3) placed in the planting hole (i.e., 2.2 g N per seedling) increased 1st-year height growth of 1+0 container Douglas-fir seedlings by 5.6 cm. Other formulations, application rates, and placement methods have not been extensively tested.

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5 Manufactured by Sierra Chemical Co. Ltd., Milpitas, Cal.

6 Manufactured by Chisso-Asahi Fertilizer Co. Ltd., Tokyo, Japan, and distributed by Westgro Sales Inc., Richmond, B.C.

7 Gates, W. B.C. Min. For. Lands, Silv. Branch, Surrey, B.C. pers. comm., 1986.

8 Benson, R. Sierra Chemical Co. Ltd., Milpitas, Cal. pers. comm., 1986.

9 van den Driessche, R. and A. Vyse. 1982. Fertilization of interior spruce at planting in the Cariboo Forest Region. B.C. Min. For. Lands. EP 859.04. Unpublished progress report.

10 Brockley, R.P. 1985. Fertilizing interior spruce at time of planting with Osmocote and Nutricote. B.C. Min. For. Lands. Sx 85131K. Unpublished data.

11 Brockley, R.P. 1985. The effect of slow release fertilizers on the early growth of interior spruce. B.C. Min. For. Lands. Sx 85132K. Unpublished data.

12 Manufactured by Mitsubishi Chemcial Industries, Ltd., Yokohama, Japan, and distributed by Estech Inc., Fairview Heights., Ill.

It is uncertain whether the responses reported for slow-release N, P and K fertilizers are due to nitrogen singly, or combinations of all three applied nutrients. Seedling responses to phosphorus applications are well documented in Australasia, Great Britain, and the southeastern United States (Everard 1974; Ballard and Pritchett 1975; Ballard 1978; Waring 1981). However, phosphorus fertilizer sources used in British Columbia (Diammonium phosphate, triple super phosphate, Mag Amp) have generally not been successful in stimulating growth of planted seedlings (Smith *et al.* 1966).[13,14,15] Foliar analysis data collected from a number of operational seedling fertilization trials throughout the interior of British Columbia showed elevated seedling foliar nitrogen concentrations 1 year following Osmocote application, but phosphorus and potassium concentrations were unchanged.[16] This is not surprising since it is unlikely that much, if any, of the phosphorus contained in a typical broadcast application of slow-release fertilizer (≤1 g P per seedling) remains in a form available for uptake by seedling roots.

If nitrogen is the element most limiting the growth of newly planted seedlings, then a slow-release, high analysis nitrogenous fertilizer may have greater potential for improving plantation performance than low analysis N, P, K products. Resin-coated urea fertilizers (39-0-0, 8-9 month release; 38-0-0, 16-month release; 37-0-0, 24-month release) are currently available for experimental use.[17] A blended product (67% Osmocote, 33% resin-coated urea), also available in various formulations (24-4-8, 8-9 month release; 24-4-7, 12-14 month release; 24-4-6, 16-18 month release), is used in forest nurseries in the southeastern United States.[17]

Another product, commercially known as SUPER 60,[18] combines the slow-release properties of melamine with the highly soluble properties of urea. The ratio of melamine to urea can be varied to produce products with different N analyses and solubility characteristics (e.g., 60-0-0; 55-0-0). Allan *et al.* (1983) reported a 59% (4.2 cm) 1st-year height growth response of 2+1 Douglas-fir seedlings to a broadcast application of SUPER 60. In a recent study with 2+0 bareroot Douglas-fir seedlings, SUPER 60 + Ca resulted in a 253% (11.6 cm) height increment response over 2 years (Hass 1987). However, application of SUPER 60 to newly planted 1+0 PSB 313 Douglas-fir seedlings caused high mortality and did not stimulate seedling height growth.[19]

Low foliar micronutrient concentrations (e.g., B, Cu, Fe) have recently been reported for many young spruce plantations throughout the interior of British Columbia.[20,21] These data indicate that an insufficient micronutrient supply may limit plantation growth on certain sites. Moreover, application of nitrogenous fertilizers may aggravate or induce micronutrient deficiencies. A slow-release Osmocote fertilizer containing micronutrients (17-6-10 + micronutrients, 8-9 month release) has recently been marketed and offers potential for use at, or shortly after, plantation establishment in the interior of British Columbia. A slower release product (17-5-10, 12-14 month release) will be available shortly.

2.2 Application Rate

Available research data indicate that application rate is not a major factor controlling the responsiveness of seedlings to fertilization. In the Cariboo, two fertilization experiments with interior spruce seedlings showed the main effects of application rate to be insignificant, although there was evidence of rate x placement method and rate x fertilizer source interactions.[22,23] Generally, the slow-release treatments (i.e., Agriform and/or Osmocote) were responsive to higher application rates, whereas the soluble fertilizers (i.e., diammonium phosphate, ammonium sulphate, and triple super phosphate) were not. In a study on Vancouver Island, 3-year

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13 van den Driessche, R. 1983. B.C. Min. For. Lands. EP 946.03. Unpublished data.
14 van den Driessche, R. and A. Vyse. 1982. EP 859.04. Unpublished data.
15 van den Driessche, R. and A. Vyse. 1982. EP 946.04. Unpublished data.
16 Winter, R. 1986. Fertilizing at the time of planting. B.C. Min. For. Lands. Sx 84115Q. Unpublished report.
17 Benson, R. Sierra Chemical Co. Ltd., Milpitas, Cal. per. comm., 1986
18 Manufactured by Melamine Chemicals Inc., Donalsonville, La.
19 Brockley, R.P. 1984. Fertilization of interior Douglas-fir seedlings with SUPER 60/urea and Osmocote at the time of planting. Unpublished data.
20 Ballard, T.M. 1984. Nutrition of planted white spruce. B.C. Min. For. Unpublished contract research report.
21 Brockley, R.P., W.R. Mitchell, and A. Vyse. 1986. Interior spruce plantation nutrition - Penticton Forest District. Unpublished data.
22 van den Driessche, R. and A. Vyse. 1982. EP 859.04. Unpublished data.
23 van den Driessche, R. and A. Vyse. 1982. EP 946.04. Unpublished data.

height response of bareroot Douglas-fir seedlings increased up to an Agriform application rate of 33.5 g N per seedling.[24] In most cases, however, the incremental gains attributable to the higher application rates were probably much too small to justify the extra costs involved.

In a study undertaken to compare Osmocote (18-6-12) and Nutricote (16-10-10) applied at 5.4 g and 10.8 g N per seedling, 2-year response data indicate that no additional height increment was achieved with the higher rate.[25] Visual observations indicated that stimulation of competing vegetation may have reduced the response potential of the heavily fertilized seedlings. In an Osmocote dosage experiment comparing broadcast application rates of 5.4, 10.8, and 21.6 g N per seedling, 50% and 100% mortality was recorded in the 10.8 and 21.6 g N treatments, respectively.[26] The combined effects of moisture stress and high salt concentrations in the rooting zone caused by warm, dry weather during the first growing season may have contributed to the poor survival of fertilized seedlings. The negative effect of fertilization on survival would probably be less pronounced under less severe growing conditions

2.3 Placement Method

At least three alternative placement methods can be considered when fertilizer is applied to seedlings at the time of planting: 1) planting hole application; 2) adjacent application (i.e., placement in a hole or slit beside the seedling); and 3) broadcast application (i.e., surface application of fertilizer around the base of the seedling). Carlson and Preisig (1981) reported the effects of fertilizer source (i.e., Osmocote and Agriform) and placement method (i.e., planting hole and adjacent) on shoot and root development of coastal Douglas-fir seedlings. All treatments resulted in a significant growth response, but the greatest height increment (+60% after 2 years) was obtained by placing Osmocote in a hole 2.5 cm upslope from the seedling. Whereas Osmocote was more stimulative with adjacent placement, Agriform performed best when placed directly in the planting hole. Planting hole placement of either Osmocote or Agriform generally resulted in heavier roots than respective adjacent treatments. Interestingly, adjacent application stimulated root growth in all zones surrounding the seedling, not just the zone in which fertilizer was applied.

Three similar studies have been undertaken in British Columbia. On Vancouver Island, broadcast application of slow-release fertilizer increased the growth of Douglas-fir seedlings significantly more than placement in a hole 15 cm from the tree.[27] In the Cariboo, sulphur-coated urea (36-0-0-17), Osmocote (17-7-12), and Agriform (21-10-5) were applied to 2+0 bareroot interior spruce seedlings at the time of planting. For each fertilizer, the following three placement methods were tested: 1) in the planting hole; 2) in an adjacent hole 15 m from the seedling; and 3) broadcast in a 15-cm radius around the seedling. Results can be summarized as follows:[28]

1. Placement of fertilizer in the planting hole clearly had a detrimental effect on survival.
2. Adjacent placement generally resulted in smaller growth response than with broadcast application. These differences were especially noticeable with Agriform.

The authors felt that placement of fertilizer in a hole closer to the seedling might have proven more effective. However, another interior spruce study in which Agriform was placed in a hole 5-10 cm from the seedling reported no measurable height growth response after 2 years.[29]

In another Cariboo study, comparisons of adjacent and broadcast methods were made for four fertilizer sources applied to containerized interior spruce seedlings. Five-year height and diameter response data indicate that the main effects of application method were insignificant, although there was evidence of a method x fertilizer source interaction.[30] As in other studies, Agriform was most effective when broadcast around the base of the seedlings. Conversely, broadcast application of soluble fertilizer sources was ineffective and significantly increased mortality.

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[24] van den Driessche, R. 1982. Slow-release fertilization of Douglas-fir at planting. B.C. Min. For. Lands. EP 946.02. Unpublished data.
[25] Brockley, R.P. 1985. Sx 85132K. Unpublished data.
[26] Thompson, C. B.C. Min. For. Lands, Nelson, B.C. pers. comm., 1986.
[27] van den Driessche, R. 1982. Slow release fertilization of Douglas-fir at planting. B.C. Min. For. Lands. EP 946.02. Unpublished data.
[28] van den Driessche, R. and A. Vyse. 1982. EP 859.04. Unpublished data.
[29] Wray, P. 1986. Direct fertilizer treatment at the time of planting. B.C. Min. For. Lands. Sx 82106N. Unpublished final report.
[30] van den Driessche, R. and A. Vyse. 1982. EP 946.04. Unpublished data.

Broadcast application of fertilizer at the time of planting probably has a greater potential for stimulating the growth of competing vegetation than either in-hole or adjacent placements. In New Zealand, all fertilizers applied at the time of planting are placed in a slit approximately 15 cm from the seedling (Ballard 1978). The adoption of this method was based on results from trials examining different methods of placement and on field experience which identified problems caused by mortality, weed competition, and fertilizer loss in run-off where fertilizer had been broadcast on the soil surface. In Japan, field trials with Japanese cypress (*Chamaecyparis obtusa* Endl.) indicated that in-hole application of 360-day release Nutricote and IBDU briquets was a reliable method of fertilizing newly planted seedlings. Seedling height growth was stimulated without increasing mortality or the severity of vegetation competition.[31,32] These results indicate that adjacent and in-hole fertilizer placement may have potential despite the generally poor success of these methods in interior spruce seedling fertilization trials reported to date. Placement of fertilizer in a hole immediately adjacent to the seedling (i.e., ≤ 5 cm) and placement of long-term (i.e., ≥ 360-day release) slow-release fertilizer in the planting hole are two options that merit investigation.

2.4 Stock Type

The largest and most consistent responses to fertilization at the time of planting have generally been obtained with container seedlings (Carlson 1981; Carlson and Preisig 1981; Burdett *et al.* 1984). Burdett *et al.* (1984) reported that broadcast application of Osmocote (18-6-12, 30 g per seedling) to interior spruce seedlings at the time of planting stimulated the 1st-year height growth of large container stock (1+0 PSB 615) but had only minor effects on bareroot seedlings. Unlike the bareroot stock, unfertilized container seedlings became chlorotic by the end of the first growing season. Chlorosis was largely prevented by fertilizing at the time of planting. The authors suggested that the difference between stock types in first-season fertilizer response may have been attributable to the 10-fold difference in RGC (Burdett 1979) measured immediately before planting. If RGC is a reliable indicator of first-season root growth, the bareroot trees, having the lower RGC, were probably more prone to moisture stress than the container seedlings. Therefore, whereas mineral nutrient deficiency appeared to be the major factor limiting first season growth of the container seedlings (as indicated by fertilization response and foliar chlorosis of unfertilized stock), moisture supply was probably the chief limitation to height growth in the case of the bareroot seedlings.

The fertilized container stock also showed improved shoot growth in the second growing season, although actual growth was less than achieved by fertilized seedlings during the 1st year. Conversely, shoot extension in the unfertilized container stock was drastically reduced in the 2nd year. These data indicate that in the second season as in the first, mineral nutrient supply was the main factor limiting the growth of container stock. The reduction in shoot growth of fertilized seedlings from the 1st year to the 2nd indicates an intensification of mineral nutrient deficiency which may have been prevented by applying more fertilizer or extending the period of nutrient release.

Whereas the bareroot trees did not respond to fertilization during the 1st year, shoot growth was significantly increased during the 2nd year. These data are consistent with the hypothesis that seedling growth tends to be limited first by moisture supply, later by the supply of nutrients. This indicates that the severity and duration of planting check can be reduced by using planting stock with high RGC and by applying fertilizer at the time of planting.

In the study reported by Burdett *et al.* (1984), it was not clear whether the superior growth response of container seedlings over bareroot seedlings to fertilizer application at the time of planting was due solely to differences in RGC or whether other physiological and morphological factors also played a role. An experiment was established in the Cariboo Forest Region (Hendrix Lake) in 1985 in an attempt to separate the

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[31] Anon. 1981. Summary of the experiment determining fertilization positions of Nutricote in new Japanese cypress land. I. Afforestation Lab, College of Agric., Shiguoka Univ., Japan. Unpublished report.

[32] Mitsubishi Chemical Industries Ltd. 1981. Studies on briquetted IBDU in practice in forest fertilization. Unpublished technical report.

effects of stock type from RGC. The project was designed specifically to investigate: 1) stock type effects (bareroot vs. container) on field performance; 2) relationship between RGC and field performance; and 3) effects of fertilization at the time of planting on field performance. Nineteen interior spruce seedlots (9 bareroot and 10 container-grown) representing a normal range of RGC values were selected. One-half of the seedlings from each seedlot were fertilized with Osmocote (18-6-12, 40 g per seedling) at the time of planting. Field measurements indicate a positive relationship between survival and RGC. Fertilization clearly had a negative effect on survival of all seedlots (66% and 48% survival for unfertilized and fertilized seedlings, respectively), but was especially damaging to bareroot stock.[33] The extremely warm, dry weather experienced throughout most of the first growing season (1985) undoubtedly contributed to the poor survival of the fertilized seedlings. Fertilization under these conditions merely aggravates stress in severely stressed seedlings, primarily as a result of the osmotic effect of high salt concentrations (Sutton 1982). The bareroot seedlings, generally having the lower RGC, were likely to have been more prone to stress than the container seedlings. A similar experiment should be repeated under less severe growing conditions.

In 1983, an interior spruce stock type trial was established at three test sites in the British Columbia Interior.[34] One-half of the seedlings from each of six stock types (1+0 PSB 313, 415, 415 copper-coated, 615, 1010, and 2+1) were fertilized with Osmocote (18-6-12, 30 g per seedling) at the time of planting. At two of the test sites, the largest fertilizer response after 3 years, both in relative and absolute terms, was achieved by the 1+0 PSB 313 seedlings. The 2+1 seedlings responded poorly to fertilization (≤ 4 cm height response after 3 years) on both sites on which they were planted. These results indicate that the initial size of seedlings has little influence on fertilizer response potential so long as the planting stock is in good physiological condition at the time of outplanting. In this regard, all nursery stock which is to be fertilized at the time of planting should be tested for RGC before planting.

2.5 Magnitude and Duration of Response

Available empirical research data indicate inconsistent responses to fertilization of planted seedlings. As a result, definitive statements about seedling fertilization response potential cannot be made. Explanations for these inconsistencies are complicated by between-trial differences such as species, seedling quality, stock type, site, season of application, site preparation, fertilizer source, placement method, and application rate. Although exact repetition of results under different conditions cannot be assured, the following discussion gives some indication of the "best" results that may be achieved by fertilizing at the time of planting.

Favourable height increments have been reported from seedling fertilization experiments in Washington and Oregon. Two-year shoot growth of fertilized Douglas-fir seedlings was 25 cm (41.8%) greater than for unfertilized seedlings (Carlson and Preisig 1981). Carlson (1981) reported a 2-year height response of 17.9 cm (23.2%) for fertilized western hemlock seedlings.

Burdett *et al.* (1984) reported that 3-year shoot growth by fertilized interior spruce container stock at their McHale River test site was 18 cm (75%) greater than that of unfertilized container seedlings and 27 cm (177%) greater than that of unfertilized bareroot seedlings. Stem volume gains by fertilized container seedlings over unfertilized container seedlings and unfertilized bareroot stock were 88% and 150%, respectively. At their Gopher Creek site, 4-year height data indicate that fertilized container seedlings grew 15.5 cm (46%) more than unfertilized container seedlings and 31 cm (166%) more than unfertilized bareroot stock.[35] Three-year fertilizer height growth responses up to 14 cm were recorded in an interior spruce stock type trial conducted at three locations in the interior of British Columbia.[36]

Miller (1981) suggested that fertilizers are generally of benefit to the tree, not the site, and that fertilizer response is best explained by accelerated movement of fertilized trees along the growth curve appropriate for the site. Thus, after seedling fertilization response has ceased, the fertilized seedlings will have seemingly jumped 1 or 2 years ahead on the curve and so will be growing at a faster rate than the unfertilized seedlings.

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[33] Vyse, A., W. Mitchell, and D. Simpson. 1986. Field performance of interior spruce: effects of stock type, root growth capacity, and fertilization at planting. B.C. Min. For. Lands. Sx 86104C. Unpublished data.

[34] Burdett, A.N. 1985. B.C. Min. For. Lands. EP 858.04. Unpublished data.

[35] Wray, P. 1986. An evaluation of methods for the production of container stock, outplanting phase. B.C. Min. For. Lands. EP 858.02. Unpublished progress report.

[36] Burdett, A.N. 1985. EP 858.04. Unpublished data.

This complicates quantifying and interpreting responsiveness of seedlings to fertilization at planting, since the continued growth improvement of fertilized seedlings is not necessarily a fertilizer effect, but rather may be a reflection of the greater size of the fertilized trees. This interpretive problem may be partially overcome by evaluating fertilizer response in terms of the relative growth rates (RGR) of the fertilized and unfertilized seedlings. Data from interior spruce seedling fertilization experiments indicate that the relative growth (i.e., ratio of current year's height growth to height at the start of the current growing season) of fertilized seedlings generally increases over that achieved by unfertilized seedlings for only 1 or 2 years following fertilization. In many cases, the RGR of fertilized seedlings falls below that of unfertilized seedlings by the 2nd or 3rd year, despite continued improvement in absolute height increment. However, it is probably unrealistic to expect larger, fertilized seedlings to maintain an advantage in RGR over smaller, unfertilized seedlings for a long period of time. An alternative, and possibly more meaningful, approach might be to compare the RGR of fertilized seedlings with that of unfertilized seedlings of a similar size. Using this technique, the apparent duration of fertilization response may be prolonged.

Response to fertilization at the time of planting is, therefore, short-lived and will not have a significant direct impact on crop yield or rotation length. However, growth response of the magnitude reported above could allow planted interior spruce seedlings to avoid the competitive influence of ground vegetation and thus achieve free-growing status earlier. Field observations indicate that the initial growth gains of fertilized seedlings may be compounded over time if unfertilized seedlings remain at a competitive disadvantage with brush for a prolonged period. On some sites, fertilizer response could make the difference between plantation success or failure.

A combination of many factors (e.g., site type, weather, stock type, seedling quality, fertilizer source, placement, and application method) govern the response potential of seedlings to fertilization at the time of planting. The permutations are innumerable. Although the combinations tested to date are by no means exhaustive, the largest responses to seedling fertilization have apparently been achieved under the following conditions (e.g., Burdett *et al.* 1984):

1. seedlings with high RGC;
2. adequate soil moisture; and
3. recent mechanical site preparation (i.e., windrowing, blade scarification).

The removal of organic matter and surface soil by mechanical site preparation may increase seedling fertilization response potential primarily as a result of nutrient depletion, soil warming, and destruction of competing vegetation. Conversely, fertilizer trials established on recently broadcast burned sites have generally been less responsive to fertilization at planting.[37,38,39,40] Provided there is favourable soil moisture, the increased availability of nutrients following burning may ensure satisfactory early growth of planted seedlings. On some sites, however, short-term favourable effects may be outweighed by significant negative impacts on long-term site productivity.

2.6 Site Preparation and Vegetation Control

Restricted shoot growth of interior spruce plantations in the years immediately following planting can put the planted stock at a competitive disadvantage with other vegetation. Fertilization of seedlings having high RGC has shown potential for reducing the severity and duration of planting check (Burdett *et al.* 1984). On sites with considerable brush potential, fertilization at planting may make the difference between plantation success and failure. However, research has demonstrated that the positive effect of fertilizer is often negated by competing herbaceous or woody vegetation, which commonly responds better than newly planted seedlings to the added nutrients (Stephens 1965; Sutton 1972; Barker 1978; Snowdon and Waring 1984).

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[37] Brockley, R.P. 1985. Sx 85131K. Unpublished data.
[38] Brockley, R.P. 1985. Sx 85132K. Unpublished data.
[39] Coates, H. 1986. Fertilization at planting of interior spruce in the Prince George Forest Region. B.C. Min. For. Lands. Sx 81108G. Unpublished final report.
[40] Wray, P. 1986. B.C. Min. For. Lands, Nelson, B.C. pers. comm., 1987.

Although this phenomenon has not yet been documented in British Columbia seedling fertilization trials, accumulated evidence strongly indicates that on certain sites broadcast application of slow-release fertilizer at the time of planting stimulates the grass and other herbaceous vegetation to the extent that growth response of the seedlings is reduced (Szauer 1986).[41,42] In one trial, the depressed 2nd-year height increment of heavily fertilized interior spruce seedlings was attributed to stimulation of vegetation competition within the fertilized radius surrounding each seedling.[41] The negative impact of competing vegetation on seedling growth performance may be greatest on sites subject to periods of moisture stress during the growing season.

Waring (1971) suggested that "in practice efficient competition control is the key to securing maximum growth rate from the time of planting since competing weeds frequently prevent fertilizer responses." Many studies have reported the beneficial effects of combining fertilization at planting with vegetation control (Smith and Schmidtling 1970; Baker 1973; Tiarks and Haywood 1981, 1986; Schmidtling 1984). In a study with slash pine (*Pinus elliottii* Engelm. var. *elliottii*) in the southeastern United States, fertilization alone and vegetation control alone were about equally effective in improving 4-year volume growth over untreated trees (increases of 65% and 54%, respectively) (Tiarks and Haywood 1981). When both treatments were applied, they interacted to increase volume increment per tree by 330%. Baker (1973) and Tiarks and Haywood (1986) also reported combined treatments to be especially beneficial, but found the response to vegetation control and fertilization was additive rather than synergistic.

Site preparation can also have a major impact on seedling growth performance because of effects on vegetation competition as well as soil nutrient, moisture, and temperature regimes, and thus may influence the response potential of seedlings fertilized at the time of planting. Process-oriented research is being undertaken in the interior of British Columbia to quantify and explain the individual and combined effects of vegetation control, site preparation, and fertilization at planting on the growth and nutrition of planted seedlings (Draper *et al.* 1985).[43]

2.7 Frost Hardiness

Applications of fertilizer at the time of planting may extend the period of active growth further into the fall season, thereby increasing the probability of frost occurring before hardening has fully developed (Alden and Hermann 1971). In a trial established at high elevation (1400 m) in the Nelson Forest Region (EP 858.04), fertilized interior spruce seedlings were heavily damaged by fall frost at the end of the first growing season (64% and 27% of fertilized and unfertilized seedlings damaged, respectively).[44] However, very little frost damage attributable to fertilization has been reported for other seedling fertilization trials undertaken in the interior of British Columbia. In fact, accumulated evidence indicates that fertilized interior spruce seedlings may be less susceptible to winter injuries (i.e., extreme cold and/or desiccation) than unfertilized seedlings.[45,46] Process-oriented research is needed to test this hypothesis.

2.8 Animal Damage

Numerous studies have documented the increased susceptibility of fertilized trees to animal feeding injuries (Gessel and Orians 1967; Oh *et al.* 1970; Radwan *et al.* 1974; Crouch and Radwan 1981; Sullivan and Sullivan 1982). In a study undertaken in southeastern British Columbia, fertilized lodgepole pine seedlings were heavily browsed by Rocky Mountain elk (*Cervus canadensis nelsoni* Bailey).[47] However, little browsing damage attributable to fertilization has been reported from seedling fertilization trials elsewhere in British Columbia.

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[41] Brockley, R.P. 1985. Sx 85132K. Unpublished data.
[42] van den Driessche, R. pers. comm., 1986.
[43] Thompson, C. 1987. A comparison of site preparation options for reforesting backlog sites in the ICH. FRDA Proj. 3.21 (EP 1001).
[44] Thompson, C. pers. comm., 1986.
[45] Brockley, R.P. 1986. The effect of slow-release fertilizer on the early growth of fall-planted interior spruce. Sx 85130K. Unpublished data.
[46] Herring, L. B.C. Min. For. Lands, Prince George, B.C. pers. comm., 1986.
[47] Thompson, C. 1982. Sx 8211N. Unpublished data.

3 ALTERNATIVE METHODS OF NUTRIENT DELIVERY TO SEEDLINGS

3.1 Incorporation at the Time of Sowing

Fertilization at the time of planting is an inefficient and expensive method of supplying nutrients to newly planted seedlings, since very little of the added fertilizer is absorbed by seedling roots. Therefore, incorporating fertilizers in the seedling root plug may be more advantageous for seedling growth after field planting than the inadvertent stimulation of competing vegetation by fertilizing at the time of planting.

A number of recent studies have tested various types and rates of slow-release fertilizers incorporated into the soil mix when container nursery stock are sown, as a means of stimulating seedling outplanting performance. In 1984, Balco Industries Ltd. examined the effects of three rates of "Sierra Blend"[48] Osmocote fertilizer (i.e., 25, 50, and 100 kg/m^3 of soil mix) on the growth of container-grown interior spruce seedlings. Contrary to product specifications, nutrient release from the resin-coated prills was very rapid, resulting in extremely high salinity buildup and excessive mortality.[49] The remaining seedlings died during cold storage. A similar trial was undertaken by Northwood Pulp and Timber Ltd. in Prince George, B.C. Various formulations of Osmocote fertilizer were tested at rates from 90 to 150 kg/m^3 of soil mix. As in the Balco trial, excessive salinity and seedling mortality were experienced.[50] Results from these two trials clearly demonstrated that under standard greenhouse temperature and moisture regimes, the release of nutrients from resin-coated Osmocote fertilizer may be too rapid for the production of acceptable container nursery stock.

Results from nursery trials indicate that a more satisfactory nutrient release rate can be achieved with Nutricote.[51] In a trial with 1+0 PSB 415 interior spruce, Nutricote (Type 360) rates up to 40 kg/m^3 of soil mix were tested with no evidence of salt injuries to seedlings.[52] Approximately 30% of the applied nutrients were released during the 1st year in the greenhouse, the remainder of which was presumably available to the seedling following outplanting. In fact, nutrient release in the greenhouse was apparently insufficient, since seedlings produced by the various Nutricote treatments were generally shorter and more chlorotic than seedlings grown under standard cultural regimes. In a companion study, a 2x2x2 factorial experiment was undertaken to determine the response of potted 1+0 Sitka spruce plug seedlings to: 1) Nutricote incorporated into the container growing medium; 2) Osmocote distributed on the soil surface at the time of planting; and 3) grass competition (plots were seeded with lawn grass at the time the seedlings were planted). Nutricote was applied at a rate of 40 kg/m^3 of soil mix (i.e., 4 g per seedling) and fertilization at the time of planting was with 30 g per seedling of Osmocote.

First-year growth data indicate that in the absence of grass competition, incorporation of Nutricote in the plug is as effective as Osmocote applied to the soil surface. The result was additive when the two treatments were combined. Grass competition, however, reduced or eliminated the response of seedlings to surface application of fertilizer. Incorporation of Nutricote in the seedling plug did not stimulate grass growth.[53] A similar experiment was recently initiated in which 1+0 PSB 415 interior spruce seedlings were grown with Nutricote (Type 360) incorporated into the soil mix at the following rates: 0, 20, 30, 40, and 50 kg/m^3 of soil mix. All treatments received regular applications of soluble fertilizers (i.e., 20-20-20 and 10-52-17) to ensure adequate growth and nutrition. After one season in the greenhouse, seedling dry weight (needle stem and root), root collar diameter, electrical conductivity of the soil solution, and foliar nitrogen concentration were significantly higher in the slow-release fertilizer treatments, indicating that at least a portion of the Nutricote was released. Seedling height, cold hardiness and RGC were unaffected by treatment.[54] Seedlings were outplanted in the spring of 1987. Another trial, in which various combinations of Nutricote Type 180, 270, and

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[48] Manufactured by Sierra Chemical Co. Ltd., Milpitas, Cal.

[49] Castonguay, G. Balco Industries Ltd., Kamloops, B.C. pers. comm., 1987.

[50] Helson, T. Northwood Pulp and Timber Ltd., Prince George, B.C. pers. comm., 1986.

[51] Gates, W. pers. comm., 1986.

[52] Burdett, A.N. 1985. Growth response of container stock to slow-release fertilizer. EP 858.09. Unpublished data.

[53] Burdett, A.N. 1986. Effect of slow release fertilizers and vegetation competition on seedlings EP 858. B.C. Min. For. Lands, For. Research Review 1984-1986, p. 13.

[54] Brockley, R.P. 1987. Effects of incorporating slow-release fertilizer in the soil mix at the time of sowing on the outplanting performance of interior spruce seedlings. EP 1014. Unpublished data.

360 were incorporated into 2+0 PSB 313 interior spruce nursery stock, was outplanted at a number of locations throughout the interior of British Columbia during the late summer of 1986.[55] Growth responses will be monitored by Regional Forest Service personnel.

3.2 Nutrient Loading

Because seedlings may have to endure harsh planting environments, there has been much interest in improving nursery cultural practices to produce seedlings of high physiological vigour that are capable of rapid early growth following outplanting. The potential for nursery stock to survive and grow after outplanting depends on many factors, one of which may be the level of seedling mineral nutrient reserves. Although a number of studies have shown a positive relationship between nursery fertilizer regime and survival and growth of nursery stock following outplanting, most do not distinguish between the effects of nutrition on growth in the nursery — which cause morphological differences (e.g., seedling dry weight, shoot:root ratio, stem caliper, mycorrhizal infection) that may influence outplanting performance — and effects on seedling mineral nutrient reserves, which could also affect growth in the field.

By adjusting late-season nursery fertilizer regimes, tissue nutrient levels can be increased to luxury levels with little effect on seedling morphology. This technique, commonly referred to as nutrient- or ion-loading, has been used by several workers to demonstrate that mineral nutrient reserves may play a role in the field survival and growth of bareroot nursery stock. In Britain, luxury uptake of nitrogen was obtained by applying nitrogeneous fertilizer to five species of nursery stock in September, when top growth had ceased (Benzian *et al.* 1974). The treatment resulted in an increase in growth of up to 18% for Sitka spruce seedlings during the first season after outplanting, with no influence on survival. On two sites, significant height differences persisted for 4 years, although the increment was small (+7%) in relation to tree size. In a similar experiment, Anderson and Gessel (1966) reported a 7% and 16% increase in survival and height, respectively, 2 years after outplanting bareroot Douglas-fir seedlings. Height differences between treated and untreated seedlings persisted for up to 5 years. Margolis and Waring (1986) reported that improved nitrogen nutrition increased growth of Douglas-fir seedlings by 37% the 1st year following outplanting. In British Columbia, Donald and Simpson (1985) reported that late-season fertilization in the nursery increased first-season height increment of lodgepole pine and interior spruce 14% and 19%, respectively. In another study, results indicated that late-season application of nitrogen (as 34-0-0) could increase 1st-year height increment of bareroot interior spruce seedlings as much as 50% over growth obtained under standard nursery fertilizer regimes.[56]

The improved field growth performance of nutrient-loaded nursery stock is likely attributable to a combination of factors including: 1) nutrient retranslocation to new tissue; 2) improved RGC; and 3) hastened bud burst following planting. (Benzian *et al.* 1974; Thompson 1983; van den Driessche 1983, 1985; Margolis and Waring 1986). However, the effects of high tissue nutrient levels on frost hardiness and drought resistance are rather ambiguous (Pharis and Kramer 1964; Christersson 1975a, 1975b; Thompson 1983; van den Driessche 1983). Moreover, Aldhous (1972) stated that early flushing could lead to frost damage following spring planting.

The amounts of nutrients, their relative proportion to each other, and the timing of their application may be the critical factors in determining the impact of nursery fertilization on frost hardiness and drought resistance (Glerum 1985).

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[55] Lloyd, D.B. Pelton Reforestation Ltd., Maple Ridge, B.C. pers. comm., 1986.
[56] Simpson, D. 1985. Late-season fertilizer effects on 2+0 bareroot seedlings. EP 866.06. Unpublished final report.

4 RECOMMENDATIONS

4.1 Operational Seedling Fertilization

First-season data from the interior spruce operational fertilization project undertaken throughout the British Columbia Interior in 1985 generally showed insignificant height and root collar diameter response to fertilization at planting (Szauer 1986).[57] Lack of response may be partially explained by:

1. the warm, dry 1985 growing season which may have resulted in moisture stress to planted seedlings;
2. inconsistencies in fertilizer application rate and placement;
3. the use of many recently slashburned sites.

However, further large-scale fertilization projects cannot be justified given our current level of knowledge regarding seedling responsiveness to fertilizer application. Available information does allow some "first approximations" to be made regarding suitable fertilizer sources, application methods, and stock types, but our ability to estimate the magnitude of the expected response, or even to predict which sites exhibit the greatest response potential, is limited.

Small-scale trials should be undertaken in specific subject areas such as:

1. development and testing of alternative nutrient delivery systems;
2. evaluation of different fertilizer sources and placement methods.

4.2 Research Trials

A number of points on the design and measurement of seedling fertilization research trials can be summarized:

- Seedling fertilization research trials should be measured for a number of years to provide a complete picture of fertilizer response potential. Yearly measurements will allow the shape of the response curve to be documented.
- Nursery stock to be used in fertilization experiments must be in good physiological condition. Therefore, the root growth capacity of seedlings should be measured immediately before planting. Whenever possible, graded planting stock of known genetic identity (i.e., half-sib or full-sib) should be used in seedling fertilization experiments to minimize non-treatment-related growth variability.
- Seedling fertilization experiments should be repeated in consecutive years on the same site to account for differences in fertilization response potential caused by yearly weather fluctuations. Foliar analysis of fertilized and unfertilized seedlings should be undertaken to estimate treatment effectiveness in terms of uptake of applied nutrients. Foliar nutrient concentration data will help determine the nutrient requirements of outplanted interior spruce seedlings, and will facilitate diagnosis of possible nutrient deficiencies.

4.3 Research Needs

Most seedling fertilization research undertaken to date has been empirical. Few studies have explored any of the mechanisms behind the observed growth response (or lack of it). Process-oriented research is needed to improve our understanding of these mechanisms and thus enhance our ability to explain inconsistencies in seedling fertilization response potential. Specifically, studies should be initiated in the following subject areas:

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[57] Winter, R. 1986. Sx 84115Q. Unpublished report.

- **Alternative nutrient delivery systems**

  Fertilization at the time of planting is an expensive and inefficient method of supplying nutrients to seedlings. Incorporation of slow-release fertilizer into the plug at the time of sowing, late-season nutrient loading, and injection of fertilizer into the plug at the time of lifting are nutrient delivery alternatives that merit investigation. Their effects on seedling morphology and physiology must be investigated.

- **Effects of seedling fertilization on root morphology and shoot:root ratio**

  Interior spruce research investigations have been limited to measurement of above-ground response of seedlings to fertilizer application. Fertilization can have a wide range of effects on root system form and development (Philipson and Coutts 1977; Carlson 1981; Carlson and Preisig 1981), and this may or may not stimulate an above-ground growth response. Moreover, any such response may not occur for several years. Changes in shoot:root ratio brought about by fertilization may have long-term effects on tree nutrient status and stability.

- **Fertilization of summer/fall planted 2+0 interior spruce**

  Because of differences in nursery culture and season of planting, a separate fertilization research strategy will undoubtedly have to be developed for 2+0 interior spruce container stock.

- **Interior spruce seedling nutrition**

  Seedling fertilization studies should be part of an integrated research strategy that would also include other factors affecting seedling growth and nutrition (e.g., nursery culture, moisture, light). Studies elsewhere have documented significant interactions between vegetation control and seedling fertilization, and substantial gains have been achieved by combining these treatments. Because of their varied effects on soil nutrient capital, nutrient availability, soil microclimate, and vegetation competition, different site preparation techniques may influence seedling nutrition and responsiveness to fertilizer application differently. Process-oriented research studies should be undertaken to investigate the nature of these interactions. Although some work is in progress, additional trials on various sites and in different biogeoclimatic subzones are required.

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